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Permeability of terrain in particle-based models of Physarum Polycephalum

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Abstract

The slime mould Physarum Polycephalum exhibits foraging behaviour to optimize its nutrient intake while preserving a minimal internal nutrient transport network. Models of Physarum Polycephalum have been constructed because it displays interesting situational behaviour which can be used to tackle various problems. We present an implementation of a particle-based model of the behaviour of Physarum concerning the problem of network optimization. We show that terrain can be implemented in a particle-based model and describe the properties such a notion of terrain should possess. In addition, we provide a useful application for the implementation of this terrain. We present networks created by virtual Physarum in a simulated environment corresponding to a real world environment and show that some networks approximate actual transport networks of this environment. The results of the experiments performed may provide insight in the effects and usage of an abstract notion of terrain in particle-based models of Physarum Polycephalum.

TABLE OF CONTENTS

1 Introduction

The single-celled multinucleate organism Physarum Polycephalum, or 'many headed slime', is a slime mould of which the vegetative stage of its lifecycle has been subject of recent research in the field of computational biology. In this stage, the slime mould endeavours to gather food by growing branches exploratively. When colonising its habitat, the slime mould tries to optimize the network of its protoplasmic veins to span the maximum number of nutrient sources, and to minimize costs of transportation and intra-cellular communication (Adamatzky & Jones, 2009). The situational behaviour of Physarum Polycephalum has been used in attempt of tackling various problems.

One of these problems is network optimization. Nakagaki, et al. have shown that Physarum Polycephalum can construct an efficient transportation network which meets the multiple requirements of short length of network and low degree of separation between food sources (Nakagaki, et al., 2004). Research has been done on understanding the complex behaviour of Physarum (Saigusa, et al., 2008) and models of – parts of - this behaviour (Adamatzky, 2010; Jones, 2011) have been presented. A modest explanation of Physarum Polycephalum, its behaviour in its vegative state, and its applications in (computational) biology will be presented in the following paragraphs, after which the place of the subject in the broad field of Artificial Intelligence will be described Finally, the scope and research questions of this thesis will be specified.

Physarum Polycephalum is a single-celled slime mould which consists of protoplasmic veins and many nuclei. The vegetative state of Physarum is also known as a plasmodium. During this plasmodium stage, Physarum Polycephalum is visible with the unaided eye and has a yellow colour. The slime mould moves according to the most common mode of locomotion seen in eukaryotic cells (Nishigami, et al., 2013); amoebic movement. It has the capability of sensing concentrations of chemoattractant secreted by food and 'branches' its body exploratively in search of it. If food is found by one of the branches, the plasmodium reinforces the branch by starting inertial movement of nuclei towards the branch, consequently destroying other less successful explorative branches. The nuclei then secretes enzymes to digest the discovered food. If multiple nutrient sources are present, the plasmodium adapts its physique to form a network that covers all the nutrient sources, minimising the total network length of the protoplasmic veins.

Recent research has shown that Physarum can anticipate to change and prepare for future changes in its environment (Saigusa, et al., 2008). The plasmodium took energy-preserving measures when Saigusa, et al. presented a repellent at a constant interval. The slime mould still exhibited this behaviour for a short while after the experiment stopped, showing some sort of intellingent adaptive behaviour.

Its exhibition of intelligent characteristics and emergent properties of complex behaviour make the many-headed-slime a suitable subject for computational modelling. The demonstration of the capability of simple maze solving by Physarum Polycephalum (Nakagaki, et al., 2000) worked as a catalyst and sparked great interest in the situational behaviour of the plasmodium, e.g. computation geometry, robotic behaviour, event anticipation, path planning and, as mentioned in the second paragraph, network optimization (see (Adamatzky, 2010) for an exhaustive overview).

The minimization behaviour of Physarum is the feature most interesting for (re)creating transport networks with this organism. Man-made transport networks could be approximated and even improved by providing a realistic model in a testing environment where Physarum can forage and develop a network such that its protoplasmic veins (branches) simulate the roads of these man-made networks. It has been shown that Physarum sufficiently approximates roads on a three-dimensional terrain as it chooses the most economic route (Adamatzky, 2012). Can a simulation of this plasmodium also exhibit such behaviour?

A simulation of Physarum plasmodium exhibiting these intelligent characteristics is a perfect example of the creation of some sort of artificial intelligent agent. Artificial Intelligence is the field of study that studies the goal of creating these intelligent agents, or more profoundly, "*The study and design of intelligent agents, where an intelligent agent is a system that perceives its environment and takes actions that maximize its chances of success*" (Russell & Norvig, 2003). An agent that simulates the behaviour of an organism, which itself exhibits intelligent behaviour, can be considered intelligent. The (behaviour of this) intelligent agent can be used as part of a larger construct to create more and smarter intelligent agents to solve certain problems – such as network optimization – in the field of AI or related fields of study.

Roughly two ways of transcribing the behaviour of Physarum Polycephalum to computer models have been used so far. The first is known as the pipeline-based model, where the behaviour of the plasmodium has been modelled with continuous mathematics. The second one is known as a particle-based model. This is a multi-agent system where agents represent 'particles' of Physarum in a reaction-diffusion environment, where the collective of these agents represent the slime mould itself. Though the pipeline-based model has been under the scope of researchers for almost 20 years, the seemingly simpler particle-based approach generates results similar to those of the aforementioned.

Recently, particle-based models have been used to study the formation of emergent transport networks (Adamatzky & Jones, 2009; Jones, 2011) created by virtual plasmodium. These models display simulated behaviour of Physarum Polycephalum concerning the formation of transport networks in a two-dimensional plane. Adamatzky and Jones suspected that problems like *"'anomalous' situations with plasmodium not imitating route M6/M74 but developing a transport link directly from Newcastle to Glasgow"* could be solved by implementing terrain in the particle-based model (Adamatzky & Jones, 2009). In addition, Adamatzky showed in his article on modelling man-made roads with real Physarum that implementing terrain as a third dimension could lead to more realistic approximations.

However, no notion of terrain has currently been implemented in the particle-based model concerning construction of emergent transport networks by Physarum Polycephalum. Could such a notion of terrain be implemented in a particle-based model to provide for useful and realistic transport networks? If so, which properties should a notion of this terrain reasonably possess to obtain a realistic and useful model?

This paper presents an implementation of the particle-based model described in (Jones, 2011) and extends it with the possibility to model terrain. We will show that it is possible to implement a concept of terrain in a particle-based model and describe the properties such terrain should possess. In addition, we will show a useful application of the model where terrain plays a key role. The application presented in this paper is concerned with the approximation of man-made road networks in which the implantation of terrain, as well as the subset of cities the author chooses to model, is crucial in the final constructed transport network.

The terminology used in this thesis will be presented in section 2, followed by a profound explanation of the particle-based model. Section 3 includes terrain in the model and will contain a formal notion of permeability of terrain. Furthermore, we will describe how terrain is modelled to provide for sufficient approximation of man-made networks in section 4. Section 5 shows the results of the experiments described in section 4. Finally, a summary of the behaviour of virtual plasmodium in a particle-based network – with implementation of terrain – will be presented in section 6, along with subjects for further research.

2 Background information on the model

This section comprises background information on the particle-based model of Physarum Polycephalum as presented in (Jones, 2011). We will introduce the terminology used in this paper to prevent ambiguity when properties of the model are discussed. A comprehensive description of the three main phases of the model is presented in section 2.1, 2.2 and 2.3. The emergent properties of the plasmodium concerning path planning and network optimization are presented in section 2.4.

The particle-based model of Physarum Polycephalum is based on a multi-agent system in which the plasmodium is simulated by a large number of identical particles, so called agents. The particles follow simple sensory- and motor rules – defined in section 2.1 – so that the collective of these particles sufficiently simulate the minimizing network behaviour displayed by Physarum Polycephalum.

The adaptive behaviour and network formation of the plasmodium is provided by the movement of the particles (agents). These agents move on a two dimensional plane we will call a simulation environment. Simulation environments are immutable when a simulation is run but can be different for every execution of the model. Figure 1 shows an example of different simulation environments.

A simulation environment is a two-dimensional discrete grid with cells we will define as patches. Patches are capable of having properties. As areas of environments in the real world are not typically rectangular of shape, – think continents, provinces and countries - a notion of accessibility of patches is constructed.

We conceptualize two abstract sets, Border and Country. Patches can be made inaccessible by adding them to the Border set. The set Border consists of the patches in the two dimensional grid which are not accessible. A patch p is inaccessible if an agent cannot move to p. Hence, an agent cannot move to patches which are member of the set Border. The set Country will be defined as the complement of Border. Thus, Country is the set of patches that are accessible. A patch p is accessible if an agent can move to p.

Figure 1: Examples of multiple simulation environments. Patches in the set Country are coloured black, while patches in Border are grey. Black areas represent accessible patches. *Left*: A simulation environment with a circular Country. *Middle:* a model of The Netherlands. *Right:* A model of England**.** All environments are in a 300 x 300 lattice.

The model is a single-substance reaction-diffusion system. By this we mean that there is only one substance of which the concentration distributes in space across the environment. This substance is defined in this thesis as some sort of chemoattractant and is secreted onto patches by agents after moving successfully. Patches hence 'own' a value of chemoattractant. Agents are able to sense this chemoattractant and base their motoric behaviour on these values, resembling ant colony optimization behaviour.

The simulation is run by a scheduler of which the flow can be defined by three core phases. The first is an initialisation step, where the simulation environment is created and virtual plasmodium is initialised in the environment. The second phase is the 'agents phase' where all agents will be randomly asked – exactly once per scheduler step – to execute their sensory- and motor functions. Finally, the last core phase is the updating of the environment where the patches in Country will be asked – again, only once and in random order – to update their values according to their diffusive and evaporation rules (section 2.2). These last two phases of the scheduler may be repeated an infinite number of times and will always come in immediate succession, meaning that value updates of the patches in Country unconditionally and immediately follow the execution of the functions for all agents. A schematic overview of the behaviour of the scheduler is shown in Figure 2 with a list of parameters of the model and their typical values.

Parameter	Description	Typical values
density	**Population as percentage of grid size**	**1-5%**
SA	**Sensory angle of the agent**	**25-70**
RA	**Rotation angle of the agent**	**25-70**
SO	**Sensory offset distance**	**5-20**
depT	**Chemoattractant deposition per step**	**5**
sMin	**Sensitivity threshold of sensors**	**1,e-6 – 1,e-9 or 0**
SW	**Sensory width**	**1 patch**
SS	**Step size**	**2 patch**
wProj	**Food stimulus projection weight**	**0.5 - 50**
wAcc	**Terrain permeability projection weight**	**0.3 - 0.8**
dampT	**Chemoattractant diffusion damping factor**	**0.15**
evap-rate	**Chemoattractant evaporation rate**	**0.9**

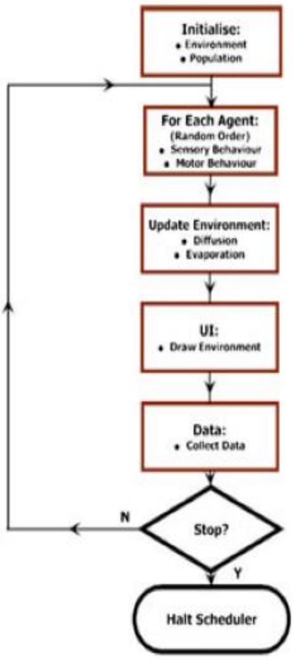


Figure 2: *Left:* table of parameters and their typical values. *Right*: schematic overview of the scheduler (Jones, 2011 p. 1351)

2.1 Agents

The agents in this model represent hypothetical units of Physarum plasmodium and occupy a single patch in the simulation environment. These plasmodium units are identical and function autonomously. An agent is able to secrete a certain amount of virtual chemoattractant onto its current patch, leaving behind a trail of chemoattractant when it moves. Due to diffusion and evaporation of the chemoattractant value of patches, this chemoattractant gradually disintegrates. Agents are attracted to this chemoattractant and follow it, positively reinforcing the trails formed. The formation of a network of chemoattractant as well as its changeability is an emergent property of the collective movement of the agents.

The behaviour of a single agent can be described by abstracting its behaviour in two stages: the sensor- and the motor stage. An agent operates as follows:

An agent occupies exactly one single patch with its body. It has 3 antennae-like sensors of length *SO* (sensory offset), of which one is placed in the direction the agent is facing, while the other two are placed at a positive and negative angle *SA* (sensory angle) relative to the heading of the agent. There is a sensor at the end of the antennae of size *SW* * *SW* (sensor width) sensing chemoattractant values of exactly *SW* * *SW* patches.

Sensory Stage: If the chemoattractant perceived in a sensor is higher than *sMin* (sensitivity threshold), save the value of the chemoattractant. The agent is asked to rotate *RA* degrees (rotation angle) in the direction of the sensor with the highest value of chemoattractant.

Motor stage: The agent is asked to locate the patch *SS* (step size) patches in front of him. If that patch is member of Country and not occupied by another agent, move to that patch. The agent secretes chemoattractant represented by the variable *depT* (chemoattractant deposition per step) if the move was successful. If the move was not successful, change the direction of the agent randomly.

A schematic representation of an agent and definition of the two stages described are shown in Figure 3.

```
[Sensory stage]
      - Sample chemoattractant values from sensors
      - if (F > FL) && (F > FR)
              - Stay facing same direction
              - Return
      - Else if (F < FL) && (F < FR)
              Rotate by RA towards strongest of FL and FR
      - Else if (FL < FR)
              Rotate right by RA
      - Else if (FR < FL)
              Rotate left by RA
      - Else
              Continue facing same direction
```

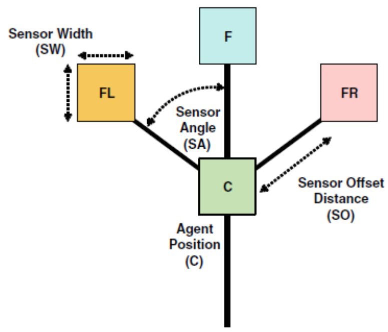


Figure 3: Particle sensory behaviour and morphology (Jones, 2011 p. 1349)

2.2 The environment

The chemoattractant values of patches will be updated once the scheduler is done with the agents phase. Updating a patch happens as follows:

The patch will be asked to diffuse its chemoattractant value to the patches in its Moore neighbourhood[1] with radius = 1. This is done by adding *1/8 * dampT ** 'the chemoattractant value of himself' to all patches in its Moore neighbourhood After all patches have diffused their chemoattractant values, all patches in the set Country will be asked to evaporate the chemoattractant. Evaporation of the chemoattractant is simulated by multiplying the patches' value by the value of *evap-rate*, effectively lowering the value of the chemoattractant. This results in chemoattractant values which approximate but never reach 0. Definitions of the methods diffuse and evaporate are given in Figure 4.

```
method diffuse(this-patch)
  moore-neighbours <- neighbours of this-patch in radius = 1
  for all moore-neighbours:
    chemoattractant of moore-neighbour <- chemoattractant of moore-neighbour +
(1/8 * dampT * chemoattractant of this patch)

method evaporate(this-patch)
  chemoattractant on this-patch <- chemoattractant on this-patch * evap-rate
```

Figure 4: High-level definition of the methods diffusion and evaporation.

The chemoattractant is visualized in the model by scaling the values to a shade of yellow, where a light shade represents high values and dark shades relative low values of chemoattractant. The chemoattractant map represents the transport network created by the virtual plasmodium.

2.3 Initialization of the model

Before the simulation is started, the simulation environment, nutrient sources, and various other parameters have to be initialized. The initialization step of the scheduler can be divided into two steps.

The first is environment initialization, where the simulation environment is initialized and chemoattractant values are reset to their initial values. Furthermore, the model provides the possibility to supply the simulation environment with fixed nutrient sources. Nutrient sources represent cities in a transport network – or more

[1] http://mathworld.wolfram.com/MooreNeighborhood.html

abstract, nodes in a graph – and are an external source of chemoattractant. These sources are circular spots of multiple patches and secrete a constant amount of the same virtual chemoattractant also deposited by agents. One significant simplification with respect to the real organism is that both food sources and the changes in flux of internal protoplasm are represented by the same diffusing chemoattractant substance (Jones, 2011, p. 1350) . The secreted chemoattractant of food sources is a weighted factor *wProj * depT* of the chemoattractant secreted by agents. If the chemoattractant value secreted at food sources is lower than the amount secreted by agents, the food sources do not affect the final network formed by the virtual plasmodium. If the concentration of chemoattractant is higher at the food sources, agents tend to migrate towards the food sources, forming a network between these points.

The second step of initialisation of the model is the deployment of the agents across the Country. Jones described three methods of agent deployment loosely corresponding to the inoculation of Physarum Polycephalum (Jones, 2011, p. 1354). The first method is *filamentous condensation*: formation of a network from random seed points in the environment. A small population size (*density of 2%*) is initialized at random locations & orientations. With *filamentous foraging*, the population is initialized form the nutrient sources while *plasmodial shrinkage* takes a different approach. This method is based on the minimizing behaviour of Physarum when food is found, shrinking its body by removing agents from the environment. The plasmodium is initialized in a circular shape with a high population size (*density = 50%*). Agents die with a probability of 0.00025 every scheduler step, gradually decreasing the size of the plasmodium.

An example of simple network formation is shown in Figure 5. The agents are initialized according to the filamentous condensation method in a circular country with three nutrient sources. Agents are initialized in a random direction (5a) after which they swiftly change direction to follow chemoattractant trails perceived by their sensors (5b). Cyclic areas in the network seem to dissolve as the virtual plasmodium contracts toward a minimal network (5 c, d, and e). Finally, the virtual plasmodium arrives in an optimal state, connecting the nutrient sources – and thus the nodes in a graph – with each other in an efficient and way (Figure 5f).

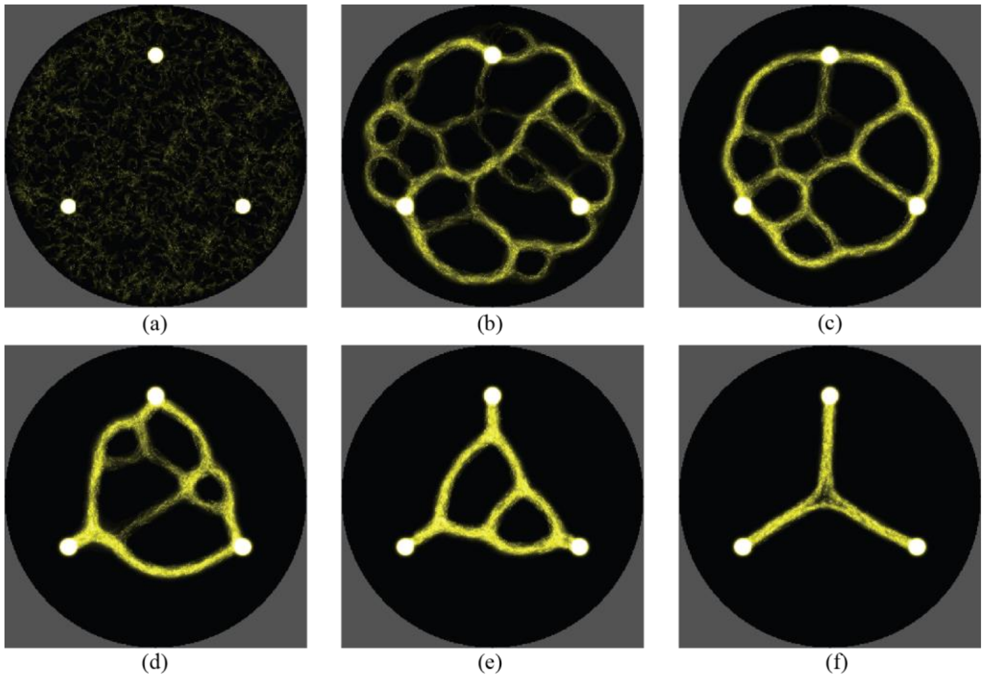


Figure 5: The yellow patches display the chemoattractant values and simulate the network created by the virtual plasmodium, the white spots are nutrient sources. Agents are initialized according to the method filamentous condensation. Density 2%, SA 65 degrees, RA 45 degrees, SO 9 patches, wProj 50, sMin 1,e-9. Simulation environment 300x300.

2.4 Emergent properties of the model

The virtual plasmodium displays similar emergent behaviour as the model described in (Jones, 2011) including collective movement, shape minimisation and internal oscillations. Created networks contain Steiner nodes when the chemoattractant concentration is low (towns or small cities) where direct connections are favoured at high chemoattractant concentrations (big cities). A higher connectivity of the network can be obtained by setting SA < RA, resulting in spontaneous branching behaviour. Contraction behaviour can be obtained by setting SA > RA. We will show in this paper that virtual plasmodium exhibits similar behaviour when terrain is implemented, though the constructed emergent transport network may differ. We present the notion of terrain and its permeability in the next section.

3 Terrain and Permeability

The notion of permeability of terrain will be described in this section. We will present the properties terrain should have in order to provide a realistic and useful model and define these properties in a formal way. In addition, we will present examples of simulation environments where terrain is implemented.

We implemented permeability of terrain as a discrete property of patches in the model. Terrain is a subset of Country where the patches in the set Terrain have an extra property. All patches in the set Terrain possess the weighted value *wAcc*. We simplified the notion of terrain in this model by only allowing one universal value of *wAcc* so we can analyse the effect of terrain more conclusively.

Terrain areas are as hard to traverse on patch p as on patch q. Thus:

$$\forall_{p,q}\ (p, q \in Terrain \mid p_{wAcc} = q_{wAcc})$$

The concept terrain in this thesis is presented as a portion of land that is evenly hard to traverse all over its area. It is an abstract concept which can be conceptualized by thinking of it as a forest, lake, or another type of terrain. The abstract notion makes implementing terrain for different modelling purposes relatively simple.

The final evaporation rate for all terrain patches will be *wAcc* times the normal evaporation rate of a patch in Country: *wAcc* • *evap-rate*. *wAcc* typically has a value between 0 and 1 as it is thus used to model terrain that is more difficult to traverse than patches without this weighted factor. Figure 6 shows sample models where terrain is implemented.

Figure 6: *Left:* Model of Armenia with terrain representing Servan Lake. *Middle*: Model of the Netherlands where Terrain corresponds to IJselmeer, Markermeer, and some waters in the province Zeeland. *Right:* Larger model of the province Zeeland. All environments are in a 300 x 300 lattice.

We use terrain in our model to simulate water as shown in the figure above. Patches part of the set Terrain are coloured blue to distinguish them from the other patches in the set Country. Terrain patches are still accessible for agents, though the increased evaporation of the chemoattractant discourages agents to go here. We will present abstract simulation environments as well as simulation environments based on real countries and provinces in the next section, in which terrain plays a key role in the creation and formation of transport networks by the virtual plasmodium.

4 Methods

We use permeability of terrain in our model to simulate bodies of water as shown in Figure 6. Does this artificial permeability of terrain provide for realistic and useful networks created in a particle-based model for transport networks? We define a realistic and useful network as an emergent transport network that approximates some real transport network to a certain degree. We will answer the question above in the results section, but first we will describe the setup of the experiments performed in this section.

Before we will analyse the applicability of environments where terrain is implemented, we present some examples of the behaviour of the virtual plasmodium around simulated water. We show that water affects the formation of transport networks in various situations. We will then show practical applications of this extension in the model by replicating various man-made transport networks.

The model environments were chosen with care where they are expected to affect the emergent creation of networks in such a way that the implemented terrain influences the collective movement of virtual plasmodium. We will show that this extension indeed provides for a profound approximation of man-made transport networks by comparing the emergent transport networks with the man-made transport networks in section 5.5.

Three different simulation environments were selected corresponding to real countries and provinces in which presence and position of terrain influences the networks created. We only adopted large bodies of water in the simulated environment to prevent noise.

The first is a model of Armenia, a country with a lake of decent size and positioned in such a way that it affects the constructed man-made road network on a large scale. The second environment simulated is the Netherlands, where its 2 provinces Zeeland and Flevoland are nearly completely surrounded by water. These provinces provided interesting complications for the virtual plasmodium. Zeeland has been selected as the third simulation environment. Zeeland is a province of interest as close to 40% of its area is occupied by water. The distribution of this large portion of water is of interest as not it is not solemnly concentrated in one area (e.g. a large lake). It is a province where many bridges are constructed between the islands, providing access to these quite remote areas. An environment has been created of this province to show that virtual plasmodium can constructs transport networks on a smaller scale than just countries. The areas and their corresponding simulation environments are shown in Figure 7.

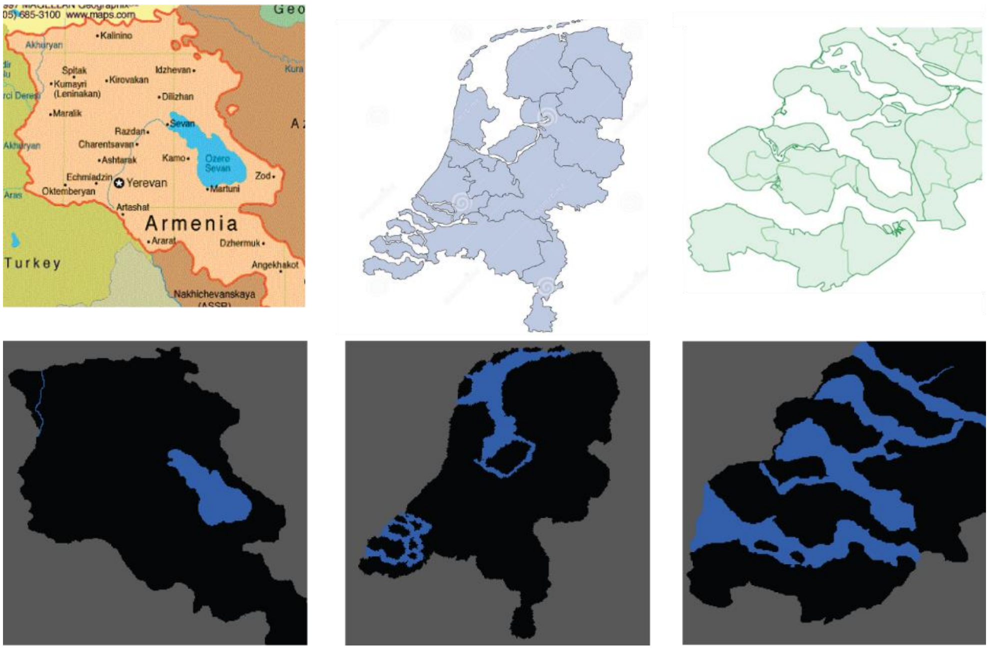


Figure 7: The simulation environments used for the simulations. *Left:* Armenia. *Middle:* the Netherlands. *Right*: Zeeland, province of the Netherlands. Source images can be found at **(Van Dorsten, 2015)** in the folder ‘maps’

Once the simulation environment has been initialized, nutrient sources, corresponding to cities in the modelled country, will be placed in the environment. Node positioning is believed to be an important factor in the formation of transport networks (Jones, 2011, p.1359). We have experimented with different subsets of the cities in the environments to provide for reasonably realistic models. An overview of the different subsets used is presented below.

Ten largest municipalities: The food sources in the model environment represent the ten largest municipalities of the country (CBS, 2014) (Armstat, 2011), where 'large' is defined by population size. Large cities are generally important cities where economic activity is high. We decided to include municipalities of adjacent provinces in the simulation environment of Zeeland as they play a significant role in the formation of the real transport network.

Province Capitals: The food sources represent the province capitals of the country modelled.[2] This is a more historical and cultural approach, province capitals are not always as important as they once were when declared capital, or vice versa. In addition, the topographical location of province capitals provides for a more evenly distribution of nutrient sources.

Manual subset: A subset of cities is chosen manually to elicit interesting emergent behaviour. Care is taken while selecting these cities, paying attention to the topographic location, population size, topographical size and economic impact of a city. This method is highly configurable which eases the provocation of emergent behaviour. This method is used to provoke behaviour and compare it to the more abstract subsets described above.

The size of a modelled city roughly corresponds to its population size relative to the population sizes of other cities simulated. The method of plasmodium initialization used is filamentous condensation. We experimented intensively with the three methods described earlier in section 2.3 and decided to construct the networks with this inoculation method.

Most parameters in the experiments were kept at a constant value to isolate the effect of the parameters which were subject to change. We experimented with the values of *RA*, *SA*, *SO*, *sMin*, *wAcc* and *wProj* while the other values – see Figure 2 for a list of parameters and their typical values - remained constant. The reader is

[2] Because Zeeland is already a province, the largest city or town (with the highest population) of its municipalities is selected. The largest cities of the municipalities of adjacent provinces are also included to provide for a more realistic model.

encouraged to experiment with the model or look at video material of the simulations (Van Dorsten, 2015). The results of the experiments will be presented in the next section.

5 Results

As described in the last section, we first present simple and abstract environments which do not directly map to man-made transport networks to exhibit the behaviour of virtual plasmodium with and without the simulated terrain. The results of the networks created in the simulated environments of Armenia, the Netherlands and Zeeland will be presented hereafter. Finally, we show results suggesting that the virtual plasmodium has the capability to approximate man-made networks in simulated environments with terrain.

Snapshots of the simulation environment and created network are selected manually and are selected because they exhibit notable changes in the process of the stabilization of the network.

5.1 Abstract environments

The simple geometrical shape of an equilateral triangle is used to setup nutrient sources for the first example. The virtual plasmodium minimizes its area while covering all nutrient sources, forming a Steiner node where the branches meet (Figure 8, top row). This is not the case when a blob of water is added to the centre of the simulation environment. In this ‘lake’, the evaporation rate of the chemoattractant is higher, resulting in patches with lower chemoattractant values, perceived by the particles as less attractive. The virtual plasmodium reforms itself around the lake in a circular shape and at times sets ground to patches with water on them, trying to optimize the network (Figure 8, middle row). When the value of wAcc is gradually increased, the plasmodium migrates onto the lake, creating the Steiner node in this centre (Figure 8, bottom row).

An example of a slightly more elaborate network is shown in Figure 9. The virtual plasmodium is again initialized following the rules of filamentous condensation. Figure 9 (b) and (c) show perfect examples of the minimization behaviour of the plasmodium, where cyclic areas are closed due to high contraction in the network. The particles slowly migrate towards the inside of the cycle, gradually closing the cyclic area by pulling its periphery towards the centre. Finally, a network corresponding to the minimal Steiner tree is constructed (Figure 9 (d)).

Figure 9 bottom row shows the same nutrient setup in a different environment. Water has been added to purposely obstruct the otherwise created minimal Steiner tree. The virtual plasmodium exhibits similar minimization behaviour as before (top and bottom row, first 3 snapshots) but remains stuck in a local optimum with one cyclic area (snapshot (h)) around the lake. These cyclic areas would normally be closed by contraction and tension of the network, gradually decreasing the size of the cyclic area. This is now prevented by the body of water, resulting in a network with higher connectivity between the nutrient sources.

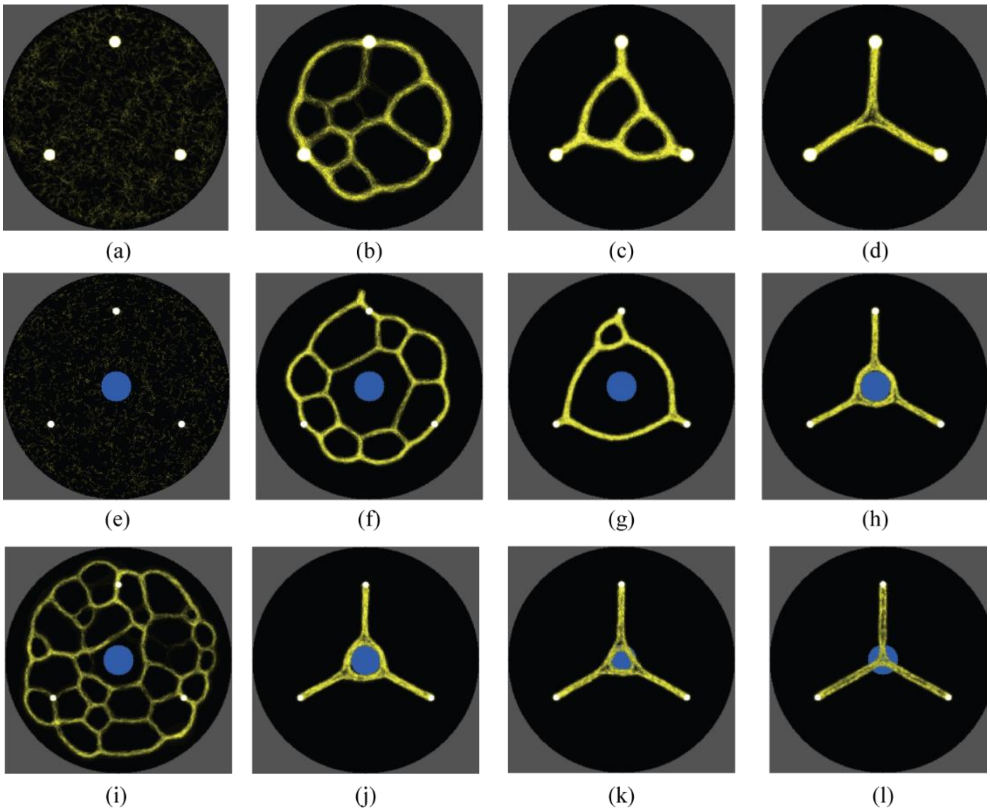


Figure 8: *Top*: Steiner tree formation with filamentous condensation, no terrain. *Middle*: Network formation with a body of water. The 'Steiner tree' cannot be constructed, the Steiner node in the middle of the three nutrient sources is blocked by water, leaving that position less attractive for the plasmodium. SA 65, RA 45, SO 11, sMin 0, wAcc 0.5, wProj 2. *Bottom:* wAcc increased until virtual plasmodium constructed a Steiner node (wAcc 0.75).

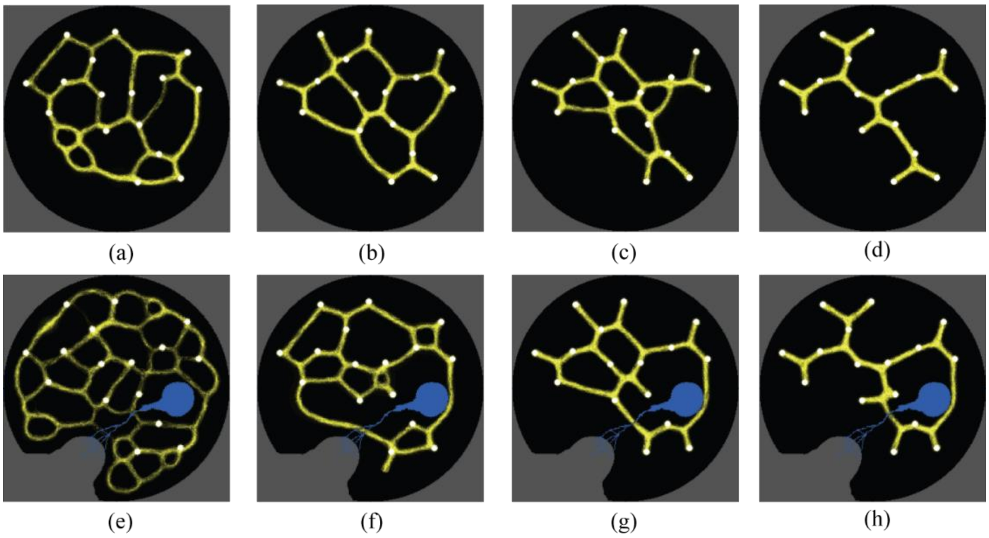


Figure 9: *Top:* formation of a minimal Steiner tree by the virtual plasmodium of a more complex set of nutrient sources. *Bottom*: formation of the network between the same nutrient sources when terrain is implemented. A cyclic area remains in the lower right corner. SA 65, RA 45, SO 11, sMin 0, wAcc 0.5, wProj 2.

The simulation environments above present interesting challenges for the virtual plasmodium. These results suggest that terrain – as it is defined and implemented in this thesis – affects networks created by the virtual plasmodium. Results showing examples of emergent transport networks created in an environment with and without terrain will be presented in the next section.

5.2 Ten largest municipalities

The results of the emergent transport networks created with the city-subset of the ten largest municipalities will be presented in this section. Results will be presented in the same order as they were introduced in the last section.

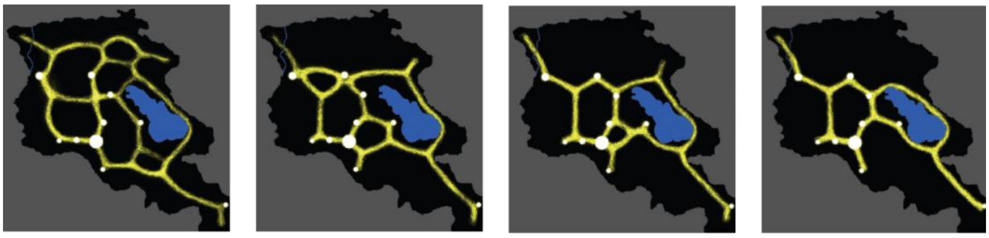
Armenia

Figure 10 shows the emergent network created by the virtual plasmodium of the ten largest municipalities of Armenia[3] (Armstat, 2011). Area minimization behaviour is displayed in the simulation, though the plasmodium has some trouble closing the cyclic connections (10c, d, left cycle). We suggest that it is caused because one of

[3] See Appendix for an overview of the modelled cities throughout the experiments

the explorative branches of the plasmodium is trapped in the top-left corner[4], changing the centroid of the network. This results in a tension on the network which is not as strong as when the branch would not be trapped. The cyclic area thus remains when the transport network reaches a stable configuration, resulting in a higher connectivity between the nodes.

The other cyclic connection in the simulation is the connection around Servan Lake (Figure 10d, right cycle). The virtual plasmodium has worked itself around the terrain and is stuck in a local optimum for area optimization. This behaviour was seen in Figure 9 as well. The question of it being a local optimum for realistic and useful transport networks is arguable because man-made networks are usually not minimal spanning trees. These networks tend to have a higher connectivity, making them more resilient to random path disconnection (One can imagine an accident blocking all traffic on a highway. Other traffic will be instructed to reroute and use another path towards its destination). We will show that the virtual plasmodium exhibits more of this similar behaviour in the next examples.



(a) (b) (c) (d)

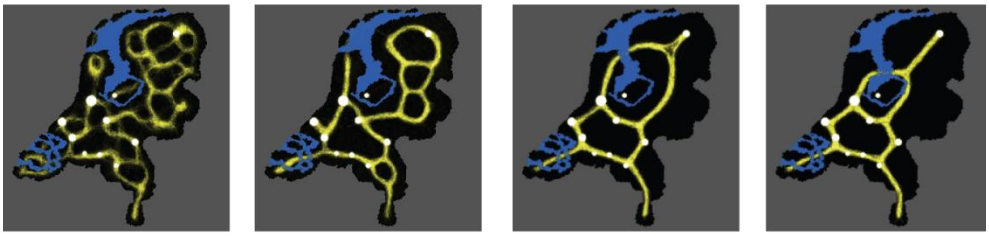
Figure 10 Emergent transport network created by virtual plasmodium of the 10 largest municipalities of Armenia, when terrain is implemented to represent Servan Lake. SA 65, RA 45, SO 11, sMin 0, wAcc 0.5, wProj 2.

[4] Branches appear to get trapped in dead ends in non-circular environments. We experimented intensively to prevent this behaviour while preserving the basic particle-based model presented in (Jones, 2011), with modest success. Suggestions for extensions of the model to prevent this behaviour are presented in section 6.

The Netherlands

The emergent networks created by the plasmodium for the ten largest municipalities of the Netherlands are show in Figure 11. The contraction towards a minimal Steiner tree is restricted by the high concentration of cities in the centre of the Netherlands (Figure 11h). The implemented water also prevents further contraction.

The unfortunate position of Almere (the city in Flevoland, the island in the centre of the simulation environment on the bottom row) seems to cause a disconnection of the main transport network in an early stage of the simulation. Increasing the value of *wAcc* to provoke connection with the network does result in a connection being made, though the network created is an instable one (not displayed). We speculate that the inter-node angle plays a key role in the formation of this unstable network, increasing the tension on the network when the node is added. One can also prevent this disconnection from happening by increasing the projection value of chemoattractant deposition at the nutrient sources *wProj*, snagging the network created around the nutrients.



(a) (b) (c) (d)

Figure 11 Emergent network created by virtual plasmodium of the 10 largest municipalities of the Netherlands. *The implemented terrain* represents the IJselmeer, Markermeer, and some waters in the province Zeeland. SA 65, RA 45, SO 11, sMin 0, wAcc 0.5, wProj 2.

Zeeland

The simulation environment of Zeeland presents different complications due to the large amount and the distribution of terrain. Figure 12 shows an additional simulation of the created network without terrain. The minimal tree found in Figure 12d is closely approximated when terrain is implemented. Terneuzen (the most southern city) seems to be disconnected from the network because of its relative distance and inaccessibility. In addition, Figure 12f shows that the three cities in the top part of the simulation environment almost suffered the same faith. We have experimented with different values of *wAcc* and *wProj* to keep cities connected to the network, with modest success. We speculate that the uneven and dispersed distribution of nutrient sources (cities) in combination with the large amount of terrain plays a role in the sparsely connected network. Results presented in the next section show that larger city-subsets provide a more stable network in the simulation environment of Zeeland.

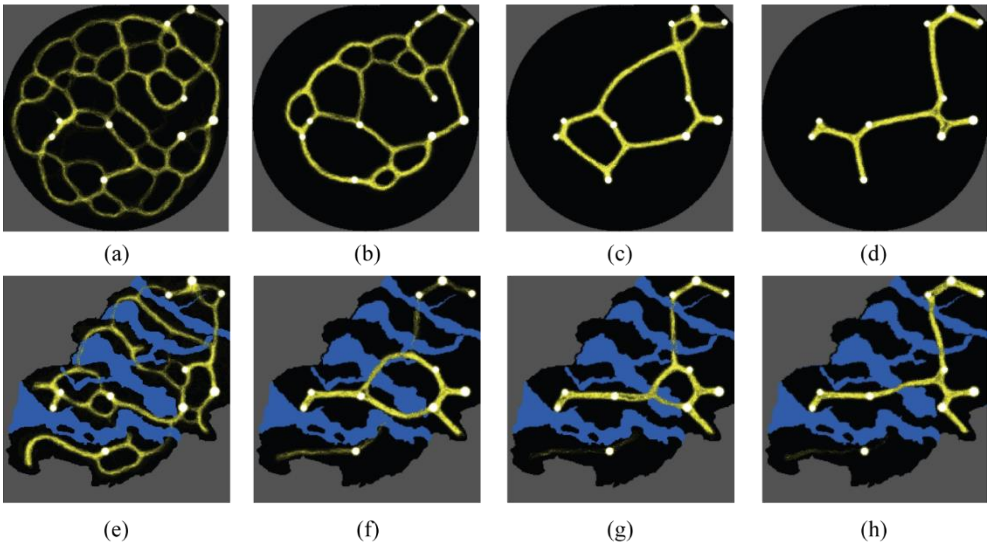


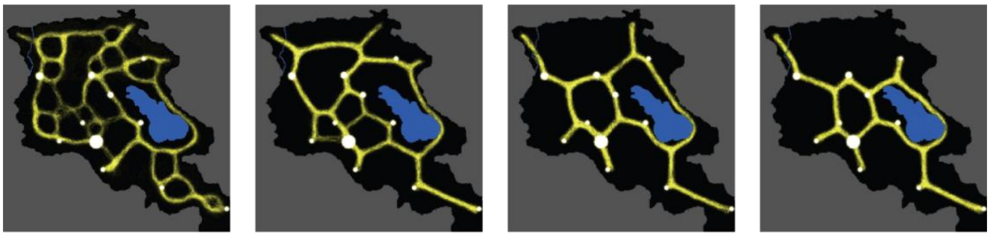
Figure 12 Emergent network created by virtual plasmodium of the 10 largest municipalities of Zeeland. *Top:* Emergent network created without terrain. *Bottom:* created transport network when terrain is implemented as bodies of water. SA 65, RA 45, SO 11, sMin 0, wAcc 0.8, wProj 2.

5.3 Province capitals

The city-subset for the following series of experiments consist the capitals of all provinces. This provides for a more even distribution of nutrient sources across the simulation environment because of the topographical locations of the province capitals. Results of the implementation of this subset is presented below.

Armenia

The topographical location of the subset of the province capitals roughly corresponds to the subset of 10 largest cities, differing in 4 cities but occupying just about the same area. Consequently, many similarities can be spotted between the final networks configurations shown in Figure 10h and Figure 13h. The same two cyclic areas are shown in these screenshots while the branch in the top-left corner remains trapped.



(a) (b) (c) (d)

Figure 13 Emergent network created by virtual plasmodium of the province capitals of Armenia. Terrain is implemented to represent Servan Lake. SA 65, RA 45, SO 11, sMin 0, wAcc 0.5, wProj 2.

The Netherlands

Only three of the cities of the last subset remain when the province capitals are chosen as nutrient sources. The distribution of the nutrient sources is more dispersed, resulting in a network completely different from the one constructed with the last city-subset.

A minimal Steiner tree is formed by the plasmodium not presented with terrain (Figure 14d). This network is closely approximated by the plasmodium initialised in the environment with terrain (Figure 14h). It is again stuck in an arguably local optimum of area minimization.

The most interesting emergent property of the network formed by the plasmodium presented with terrain is the formation of the path closely resembling the afsluitdijk (English: closure dike, Figure 14h). This is a dike that, amongst other thing, supports one of Netherlands’ major highways and provides an important connection between the provinces North Holland and Friesland. This connection is not formed when a virtual plasmodium is not presented with the terrain (Figure 14d).

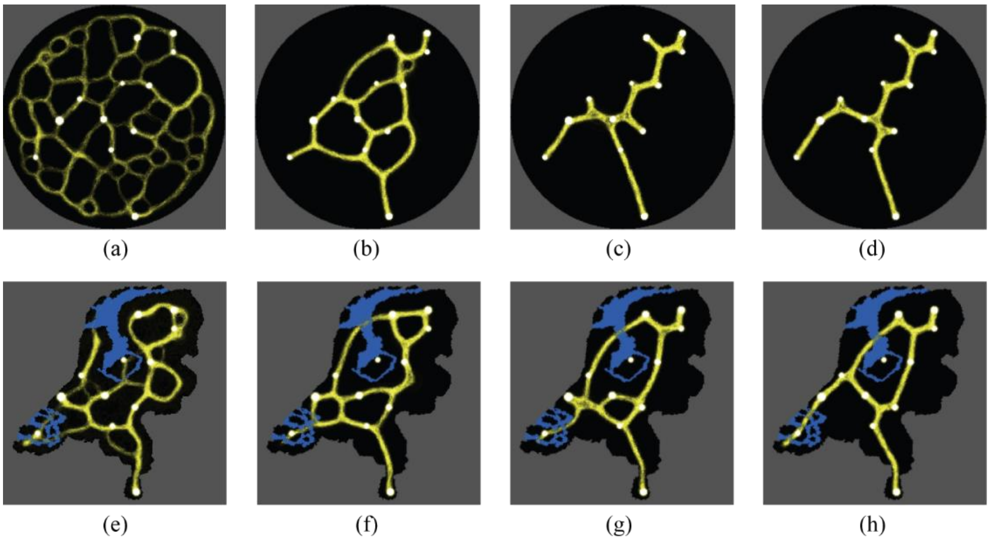


Figure 14 Emergent network created by virtual plasmodium of the capitals of the twelve provinces of the Netherlands. *Top:* Emergent network created without terrain. *Bottom:* created transport network when terrain is implemented to represent the IJselmeer, Markermeer, and some waters in the province Zeeland. SA 65, RA 45, SO 11, sMin 0, wAcc 0.7, wProj 2.

Zeeland

Simulating a network between the province capitals of Zeeland is not that interesting as Zeeland is a province itself, resulting in a network with only one node. We chose to take the largest cities of the municipalities in the simulation environment and let the plasmodium construct a network between these nodes. The results are displayed in Figure 15.

Both the network displayed in Figure 15d as the network in Figure 15h show multiple cyclic connections. The increased connectivity of the network is due to the lower SA angle in combination with the high density of nutrient sources, decreasing the tension across the network. This provides for a more fine-grained network which sufficiently approximates the actual road network in Zeeland. We also increased the density value to 3% to prevent the otherwise sparsely created paths in the network.

The transport network displayed in the bottom row approximates man-made in a realistic way. The increased connectivity and sparsely created ‘bridges’ over narrow portions of water show a good replication of the actual road network of Zeeland which we will display in section 5.5. We will extend this subset, which provides for a more fine-grained network in combination with the parameter settings, in the manual set of cities.

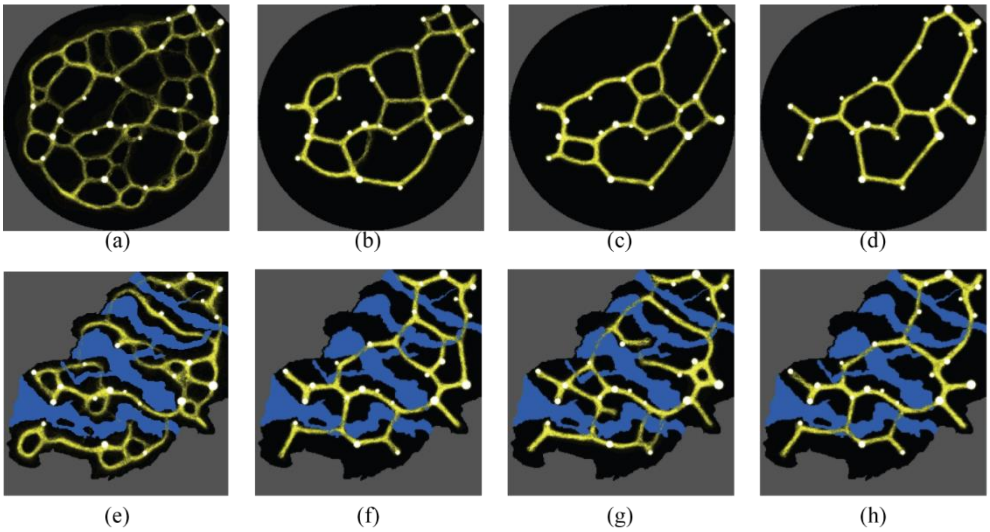


Figure 15 Emergent network created by virtual plasmodium of the province capitals of the municipalities of Zeeland and its visible municipalities of neighbouring provinces. *Top:* Emergent network created without terrain. *Bottom:* created transport network when terrain is implemented as bodies of water. Density 3% SA 55, RA 45, SO 11, sMin 0, wAcc 0.75, wProj 2.

5.4 Manual subset

Care should be taken when a manual subset of cities is chosen as manual subsets are model-specific. The following subsets of cities in environments are based on the subsets described in the previous section and are constructed to provoke realistic and useful emergent transport networks.

Armenia

The manual subset of cities in Armenia is a copy of the province capitals, as this set already profoundly approximates the road network in Armenia. We extended the subset with 2 extra nodes to create a more detailed replication of the real network. The new nodes implemented were both already in the close neighbourhood of paths created in the last section, only refining the shape of the network.

The network created by the virtual plasmodium is hence practically identical to the network created with the province capital subset. The careful reader may have noticed that the final configuration of the network could be improved by creation of a path between the cities Artashat and Yerevan (see Appendix) instead of the road created from Artashat to a certain spot in the network (Figure 16d, most bottom-left nutrient source).

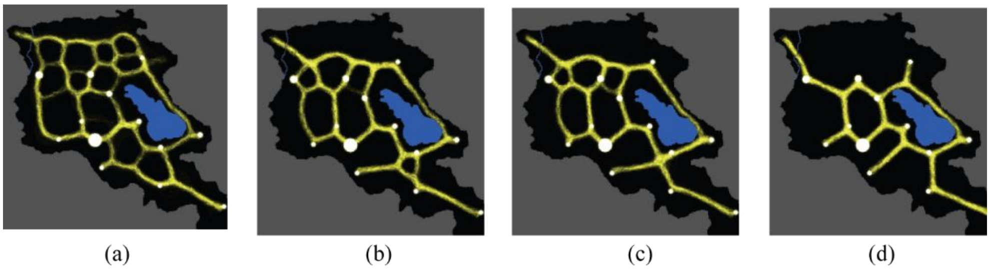


Figure 16 Emergent network created by virtual plasmodium of a manual subset of cities of Armenia. Terrain is implemented to represent Servan Lake. SA 65, RA 45, SO 11, sMin 0, wAcc 0.5, wProj 2.

The Netherlands

The manual subset of cities of the Netherlands contains cities from both city-subsets. The subset is designed to provoke a better approximation of the position of the afsluitdijk, as well as distributing the cities better across the simulation.

We increased the value of *wAcc* to show that it is possible to let the plasmodium adopt the nutrient source in the province Flevoland to its network. The Lower *SA* value is also crucial for the addition of this node, which result in increased connectivity, best seen in 17c, more closely corresponding to real man-made networks. The final configuration seen in 17h is a network where the emergent minimization property of plasmodium is of an arguably negative influence when we look to approximate real transport networks with their fine-grained structures.

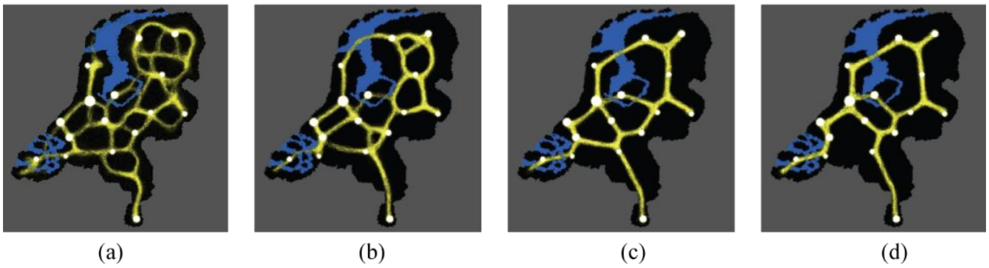


Figure 17 Emergent network created by virtual plasmodium of a manual city-subset the Netherlands. Terrain is implemented to represent the IJselmeer, Markermeer, and some waters in the province Zeeland. SA 55, RA 45, SO 11, sMin 0, wAcc 0.8, wProj 2.

Zeeland

The manual subset of cities in the simulation environment of Zeeland is, just like the manual subset of Armenia, based on the province capitals-subset. We extended this subset and experimented with different values of *SA* and *wAcc* to provide for a realistic, connected network.

The final network created with terrain has a reasonably different structure than the one created where no terrain is implemented (Figure 18d, h), suggesting that the (relatively low) value of *wAcc* impacts the created network. The added nutrient sources result in a network that approximates the real transport network of Zeeland.

The emergent network of Zeeland created with the manual subset – and terrain implemented – has shown to be quite instable when the experiments were run. The virtual plasmodium tends to structure his network with a high amount of Steiner nodes, sometimes disconnecting nodes where inter-node angles are the least optimal. This is unacceptable when recreating and approximating man-made networks and should be prevented or resolved. Settings which could improve the connectivity to prevent this from happening are decreasing the network tension, increasing the permeability of terrain and decreasing the size of the sensory area by lowering the value of *SA*. Finding optimal solutions in the parameter space as well as finding a well-defined abstract city-subset to more profoundly approximate man-made networks could be a subject for further research.

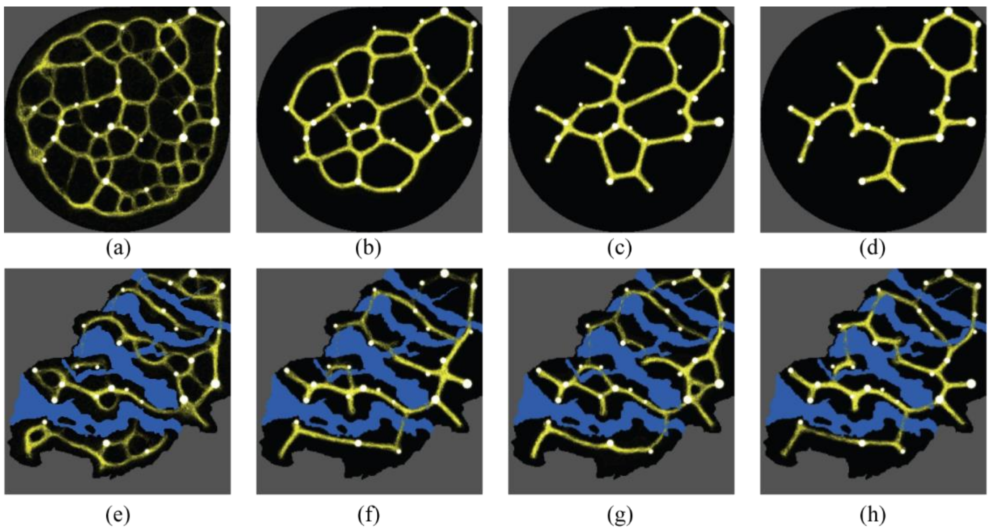


Figure 18 Emergent network created by virtual plasmodium of a manual subset of the cities of Zeeland, including parts of adjacent provinces. *Top:* Emergent network created without terrain. *Bottom:* created transport network when terrain is implemented as bodies of water. SA 55, RA 45, SO 11, sMin 0, wAcc 0.75, wProj 2.

5.5 Physarum transport networks vs man-made transport networks

In this section, we compare some of the emergent transport networks created by virtual plasmodium in the last section with man-made networks. The roads connecting the cities in man-made networks are constructed with data from Google Maps, and resemble the main roads connecting the cities. Directed routes have been selected as much as possible, intersections of roads have only been implemented in the abstract representation of man-made networks when its presence is of significant influence. An example of one of these intersections is presented in Figure 19a, where an intersection over water exists between Zierikzee, Oude-Tonge and Steenbergen.

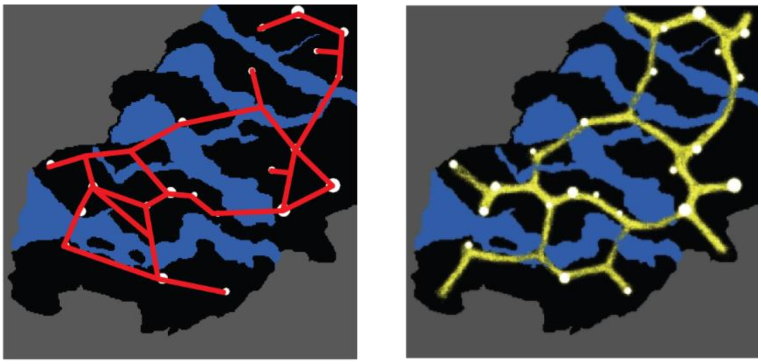
The examples below illustrate the ability of the model to approximate real transport networks. We will describe the attributes of the emergent networks in relation to the man-made networks in the following paragraphs.

Province capitals of Zeeland

The network created by the virtual plasmodium, when presented the city-subset of province capitals, approximates the man-made network of Zeeland in a decent way (Figure 19). A network with relative high connectivity is shown in both networks. Many connections shown in Figure 19a are also created by the plasmodium.

An example where the plasmodium constructs non-existent roads is the bridge constructed between Hulst and Kruiningen (21b, bottom-right corner). We suspect that this connection is created because connections to other countries are not modelled. The traffic would normally be routed from Hulst via Belgium and Bergen op Zoom towards Kruiningen (or vice versa). This is not shown in Figure 19 as this road is outside of the simulated area.

An example of connections the plasmodium does not create is the road connecting Breskens and Vlissingen (bottom-left corner). We suspect this is because of the trapped branch in the bottom-left corner, pulling the network in this direction and not exploring the area where this road should be created.



(a) (b)

Figure 19 Approximation of man-made transport networks by virtual plasmodium simulated on the city-subset of the largest cities in the municipalities of Zeeland and neighbouring provinces.

Armenia: 10 largest cities and province capitals

We selected the networks created of the first two subsets in the simulation environment of Armenia to illustrate some flaws in the approximation of man-made networks. When we look at the emergent network in Figure 20b, we see a quite different network when compared with the network created by men. The plasmodium constructs a road around the less permeable area and is stuck in a local optimum, not minimizing its area. One can suggest that the emergent network does not approximate the man-made network sufficiently because the network created differs in shape, connectivity and efficiency. The path created at the right side of the lake in Figure 20b provides no improvement for a transport network between the ten largest cities of Armenia.

When the city-subset of province capitals is chosen, this path suddenly augments the emergent created network, approximating the real network in a sufficient way (Figure 20c, d). The path at the right side of Servan Lake is now a good option to go from Ijevan to Kapan (top-right to bottom-right).

These two examples of fairly similar networks on different subsets suggests that the city-subset chosen is of significant impact on the approximation of man-made networks.

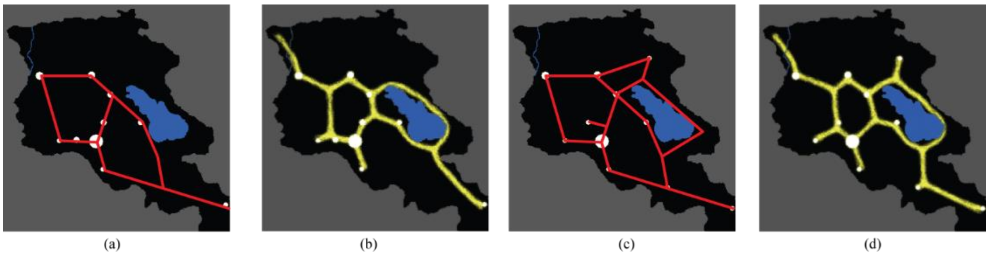


Figure 20 (a) and (b): Approximation of man-made transport networks by virtual plasmodium simulated on the city-subset of 10 largest cities. (c) and (d): Approximation on the subset of province capitals.

Manual Subset of the Netherlands

Figure 21b shows the network created in the simulated environment of the Netherlands by virtual plasmodium when presented with the manual subset. There is definitely resemblance with the actual transport network of the Netherlands, though the network created by plasmodium lacks visibly in connectivity. Utrecht is a central point in the Netherlands with many direct connections from all over the country. The plasmodium fails to construct such connections in its final stable state, as the displayed tension on the network result in the contraction of these cyclic areas (Figure 17c).

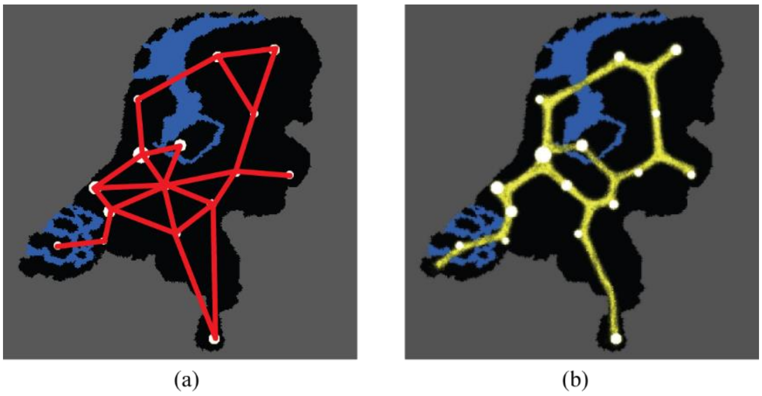


Figure 21 Approximation of man-made transport networks by virtual plasmodium simulated on a manual city-subset of the Netherlands.

Some emergently created networks presented in this section have shown to sufficiently approximate man-made networks to a certain degree. The city-subset is suspected to be of critical influence when we consider the degree of similarity between man-made networks and virtual plasmodium networks, as it seems that the created networks do not guarantee a good approximation. We suspect that the influence of many other parameters in the real world, not implemented in the model, influence the formation of real transport networks. Modelling these other parameters could improve the usefulness of emergent created networks by virtual Physarum Polycephalum, providing for more realistic networks and closer approximations of real transport networks.

6 Discussion

Prior research documented the emergent properties concerning network optimization of virtual plasmodium in particle-based models based on the slime mould Physarum Polycephalum. It was shown that a particle-based model of virtual plasmodium is capable of displaying area minimization and network optimization behaviour in a simulated environment without terrain, similar to the behaviour of Physarum Polycephalum.

In this thesis we extended the particle-based model of Physarum plasmodium with a notion of terrain to show that terrain can be used to create realistic and useful transport networks based on the network optimization behaviour of Physarum Polycephalum. We presented a uniform value of permeability as a property of terrain and conducted experiments to give insight in the behaviour of virtual plasmodium around terrain.

Results of the experiments implied that virtual plasmodium displays similar emergent behaviour when presented with terrain as to when it is not presented with terrain when optimizing transport networks. A practical application of the extension was presented where the plasmodium is used to approximate man-made networks.

The experiments suggested that the virtual plasmodium has the capability to sufficiently approximate these networks. It was shown that the virtual plasmodium constructed many paths similar to those of man-made networks. The displayed behaviour of the virtual plasmodium around terrain created the impression that the terrain affects its behaviour without losing its emergent properties. This implies that implementing terrain in particle-based models of Physarum is an interesting contribution to the area of Artificial Intelligence concerned with simulating intelligent characteristics of organisms, as in thus provides a seemingly more close approximation of the behaviour of real Physarum Polycephalum.

The location and distribution of nutrient sources were speculated to be of great influence on the created networks and their applicability to approximate real networks. The results suggest that finding a well-chosen subset of cities could provide significant improvements in the approximation of man-made networks. This provides a subject for further research. Another subject for further research is the problem of branches of virtual plasmodium trapping themselves in corners. Explorative branches of real Physarum Plasmodium perish when no food is found. Further work could include an implementation of such behaviour of virtual plasmodium.

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Available at: https://github.com/sandervandorsten/Physarum-Polycephalum-Thesis.git

The code and videos can be accessed and downloaded at:
https://github.com/sandervandorsten/Physarum-Polycephalum-Thesis.git
If the reader is by any means unable to access the code or simulations, he is encouraged to send an email to the address of the author: sandervandorsten@gmail.com

Appendix

A. The modelled cities and the corresponding locations

Armenia

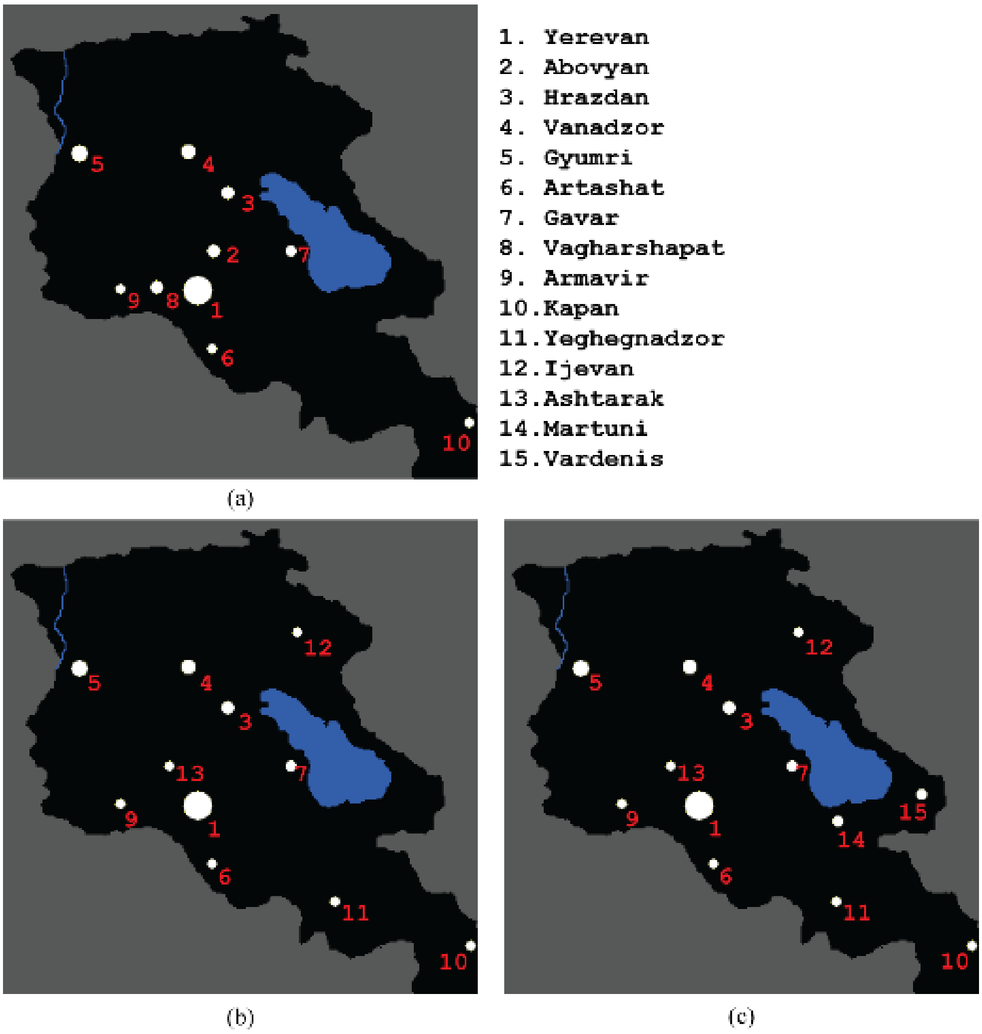

Figure 22 Cities and their corresponding locations in the simulation environment of Armenia. (a) Ten largest cities. (b) Province capitals. (c) Manual subset.

The Netherlands

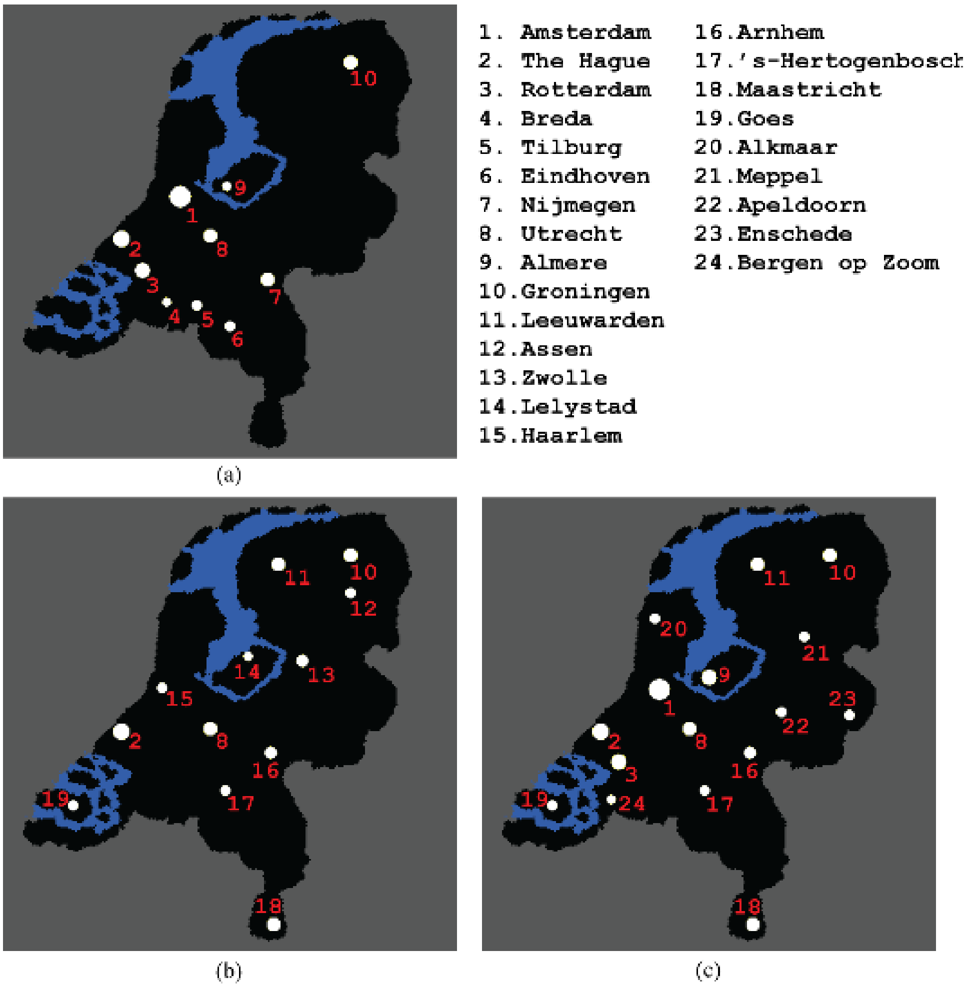

Figure 23 Cities and their corresponding locations in the simulation environment of the Netherlands. (a) Ten largest cities. (b) Province capitals. (c) Manual subset.

Zeeland

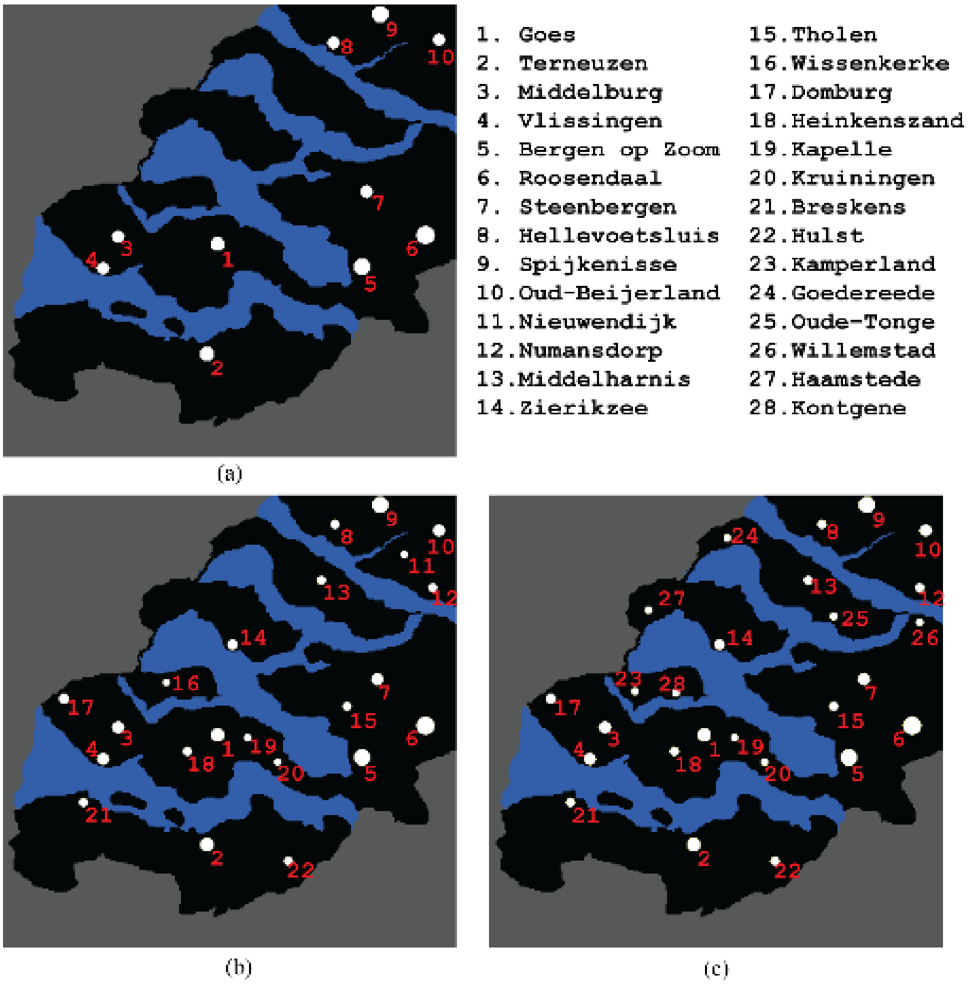

Figure 24 Cities and their corresponding locations in the simulation environment of Zeeland. (a) Ten largest cities. (b) Province capitals. (c) Manual subset.